Plasma Experiment for Planetary Exploration (PEPE) on DS1[1]

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Abstract The Plasma Experiment for Planetary Exploration, PEPE (pronounced PEP), is a space plasma energy, angle, and mass/charge spectrometer now taking data aboard the Deep Space 1 (DS1) spacecraft. PEPE required several advanced technologies and specialized construction techniques to meet its targeted cost, schedule, mass, power, and volume reductions compared to previous plasma sensor packages such as the NASA Cassini mission Plasma Spectrometer (CAPS). It was designed to validate technologies and techniques for these resource savings so that future plasma instrumentation can use fewer resources and continue to have frequent access to space. PEPE was also designed to monitor the effect that the ion engine on DS1 has on the spacecraft environment and determine the impact of ion engines on future scientific instrumentation and measurements. PEPE has produced both high quality data and science, fully demonstrating that its new technologies can produce a viable instrument compatible with an ion propelled spacecraft.

TABLE OF CONTENTS

1. INTRODUCTION

The NASA New Millennium Program (NMP) was started in 1995 to validate the use of new technologies in spacecraft design and implementation with the purpose of ultimately making possible space missions that are truly smaller, cheaper, faster, and better. The first in the Deep Space series of test missions, Deep Space 1 (DS1), was designed to test several technologies including an ion engine and auto-navigation . To fully test such a mission it was necessary to demonstrate that the spacecraft could self-navigate to a planetary body and reach it with the savings in fuel and time predicted to be possible with the use of an ion engine. Space plasma research couples very well into such a mission. Planetary bodies provide rich and relatively new ground for them scientifically, the environment induced around the spacecraft by the ion engine plume, and the viability of future scientific missions using ion engines with space plasma instruments all together provided a unique opportunity to validate new space plasma instrumentation in ways that will have a significant impact on the design of future science missions.

The Plasma Experiment for Planetary Exploration, PEPE, has worked successfully since December 1998 on the Deep Space 1 (DS1) spacecraft. PEPE analyzes the direction and energy of incoming ions and electrons and, in addition, measures the mass/charge of incoming ions. A space plasma analyzer of this type is usually used for scientific analysis of ambient plasmas such as the solar wind and the environment near a planetary body, but it can also analyze what is being ejected by an ion engine by monitoring a small fraction of its plume and effects on the spacecraft. DS1 s planned visits to planetary bodies such as comets, its time in the solar wind, and the plasma environment produced by its ion engine provided an ideal testbed to develop and test new space plasma instrumentation. The solar wind provides a well known environment for instrument calibration and the planetary body flybys and ion engine provide scientific opportunities for investigation of new plasma environments and their effects on the solar wind.

PEPE was designed to demonstrate six new technologies that have the potential to revolutionize the construction of space plasma analyzers. The six new technologies are: miniaturized time-of-flight (TOF) section; confocal ion and electron optics; high speed chip-on-board electronics; advanced power supplies; highly integrated electronics, power supplies, and optics; and coatings and surface treatments for higher integration and lower mass.

Plasma analyzers are traditionally as complicated to build as, for example, large imaging instruments and employ techniques such as high voltage/high electric field design; several different surface coating and polishing treatments; ultra-thin (~50 thickness) carbon foils; very low power, high speed, large dynamic range electronics; single particle detectors which are contamination sensitive; and

Figure 1 PEPE is visible on DS1 in the upper left-hand corner

sophisticated data processing and compression. PEPE required all of these elements but employed them in new ways and combined them with advances in electronic packaging and improvements in mechanical and electro-optical design that allowed it to be much smaller and cheaper than previous instruments.

PEPE was built by collaboration between Los Alamos National Laboratory (LANL) and Southwest Research Institute (SwRI) with the addition of some micro-machined calorimeters from Stanford University. The build time from start of funding to delivery was just over two years, which is extremely fast for a complex plasma instrument of this type, particularly one involving the many new technologies which PEPE used. The time-to-delivery is, however, a major factor in the overall cost of a space instrument. PEPE was only possible because the design tools, test and fabrication facilities, and expertise were already in place at each institution. Much of this expertise was devoted to making judgements and decisions about the handling and mitigation of risk in rapid development of the sophisticated PEPE technologies and instrument. Each institution has a tradition of scientific investigators who are experienced in instrument development and who work as the project task manager, which is often a separate function elsewhere. This structure allows a quick turn-around from instrument concept through hardware fabrication because all aspects of design are considered together allowing tasks to be assigned to designers who carry forward parts of an integrated plan. PEPE also benefited from skilled designers and technicians with many years of broad experience in similar types of instrumentation.

Another factor in the rapid development of PEPE was a very good working relationship with the DS1 project. New Millennium Project members inside and outside DS1 flight team worked to simplify integration issues and streamline the qualification and review process as much as possible. Without this sort of cooperation and dedication to the flight validation of new technologies for space missions, an instrument such as PEPE would not be possible.

PEPE is now validated for use on other missions, and we hope that it will fly on many future scientific spacecraft. In this paper we will detail some of the design techniques that made PEPE possible and show a small subset of the data it has produced. PEPE was designed as a general-purpose plasma instrument to measure the energy/angle spectrum of electrons and the energy/angle/mass spectra of ions. This alone would make PEPE of good candidate for Deep Space 1 because the spacecraft will be passing several small planetary bodies that give off ionized gases that are of the intense scientific interest. PEPE can contribute significantly to the scientific questions concerning those bodies by studying the composition of the material released and the way in which it interacts with the solar wind. In addition, the ion engine on Deep Space 1 produces a cloud of neutral and ionized gas around the spacecraft that a plasma spectrometer such as PEPE can measure and use to diagnose the formation of that cloud, its effects on the spacecraft[1], and possibly detect whether or not the engine is functioning nominally or suffering some degradation. When the xenon expelled from the ion engine begins to sputter away the metal grids inside it, PEPE has been able to detect molybdenum ions in the charged xenon cloud around the spacecraft. Thus PEPE was chosen for DS1 both because of its science and diagnostic capabilities and its new technology. Figure 1 shows PEPE mounted on the spacecraft so that it has an almost 270° view of space but does not reside so close to the ion engine that it might be damaged by high fluxes out of the engine. PEPE is located on a bracket at the upper (+Z) end of the +X-Y panel of the spacecraft so that the central plane of the FOV lies in the XZ plane. This gives PEPE access to both the nominal solar wind direction and to boresight direction of the imager aboard DS1, the Miniature Integrated Camera and Spectrometer (MICAS).

2. OVERVIEW

Figure 2 shows a photograph of the PEPE instrument. PEPE is designed as a general purpose plasma sensor capable of measuring electrons and mass-resolved ions over most of particle phase space from 8 eV to 33,500 eV. Because 3-axis stabilized spacecraft pose a problem for complete coverage of all possible plasma arrival directions, PEPE is also designed with a field-of-view (FOV) covering

a solid angle of 2.8 π steradians. PEPE heritage comes largely from work at the two collaborating institutions: SwRI development of miniaturized electrostatic analyzer optics [2] and LANL development of 3-dimensional linear electric field (LEF3D) time-of flight (TOF) mass spectrographs [3] and [4]. Our chief objective was to build an instrument with performance comparable to that of the NASA Cassini mission Plasma Spectrometer (CAPS) on which LANL and SwRI had collaborated (together with other institutions [5]), but with significantly lower resource requirements. In order to achieve this goal the CAPS electrostatic optics were either modified or entirely redesigned and miniaturized. This required the introduction of several new methods and technologies including high resistance coatings applied to ceramic TOF cylinders, the use of metal-plated plastics in place of metallic parts, and novel optical/electronic packaging methods. Also, a large (3.6 kg) stepper motor actuator used to rotate the entire 20 kg CAPS instrument was replaced by an electrostatically scanned FOV.

PEPE is also a combination of several sensors in one but they are not separately packaged as they are in earlier instruments. For example CAPS has seven major subsections including three individual sensors packaged separately. PEPE has two of the three sensors and all of the other major CAPS subsystems, except for the actuator, in a single, highly integrated package. This eliminates significant unnecessary mass which is needed in individual module packages to provide radiation and micrometeoroid shielding as well as structural support. External cabling and connectors and any additional shielding they require are also eliminated.

The PEPE electro-optic and mechanical layout, shown in Figure 3, is cylindrically symmetric about the central vertical axis and the electro-optics consist entirely of electrostatic elements. The optical system consists of three main functional elements: angular deflection optics, energy/charge analyzers, and the LEF3D TOF optics. In order to protect instrument components such as detectors, carbon foils, and highly resistive surfaces that are sensitive to particulate and chemical contamination, PEPE is fitted with a sealed cover through which N_2 purge gas is flushed. The cover is removed before the rocket fairing door is closed before launch.

Instrument Description

Ions and electrons enter the PEPE optics through a grounded toroidal grid that defines the external acceptance aperture of the instrument. The grid also terminates the electric fields within PEPE. Immediately inside the grounded grid, ions and electrons experience an electric field that deflects them into the acceptance volume of the top-hat electrostatic analyzers. The name top-hat applies to the toroidal analyzer plates and their entrance aperture which is horizontal in Figure 3 [6]. Usually only one set of curved analyzer plates is used and, with the entrance aperture looks rather like a rounded top-hat. The deflection electric field is generated by two opposing, cylindrically symmetric, toroidal electrodes. Equal voltages of opposite polarity are

applied to the deflection electrodes so that, for example, ions coming from above the symmetry plane are deflected downward into the upper top-hat aperture, while electrons coming from below the plane are also deflected toward the upper apertures. The top-hat analyzers, one for ions and one for electrons, are positioned so that their apertures are located symmetrically above and below the central plane. As ions and electrons enter the region of the top-hat analyzer electric fields, they are deflected down and up respectively into their individual electrostatic energy analyzers. By changing the deflection voltages PEPE s field of view can be moved from +45° to -45°. For example if ions are entering from -45° then electrons will enter from +45°. The 360° azimuthal direction around the axis of PEPE is continuously viewed but there is usually some blockage because of the spacecraft body. The energy of the ions or electrons that are allowed to enter is determined by the voltage on the curved plates which, like the deflection voltages is continuously swept. Up to this point the optical systems are identical for ions and electrons.
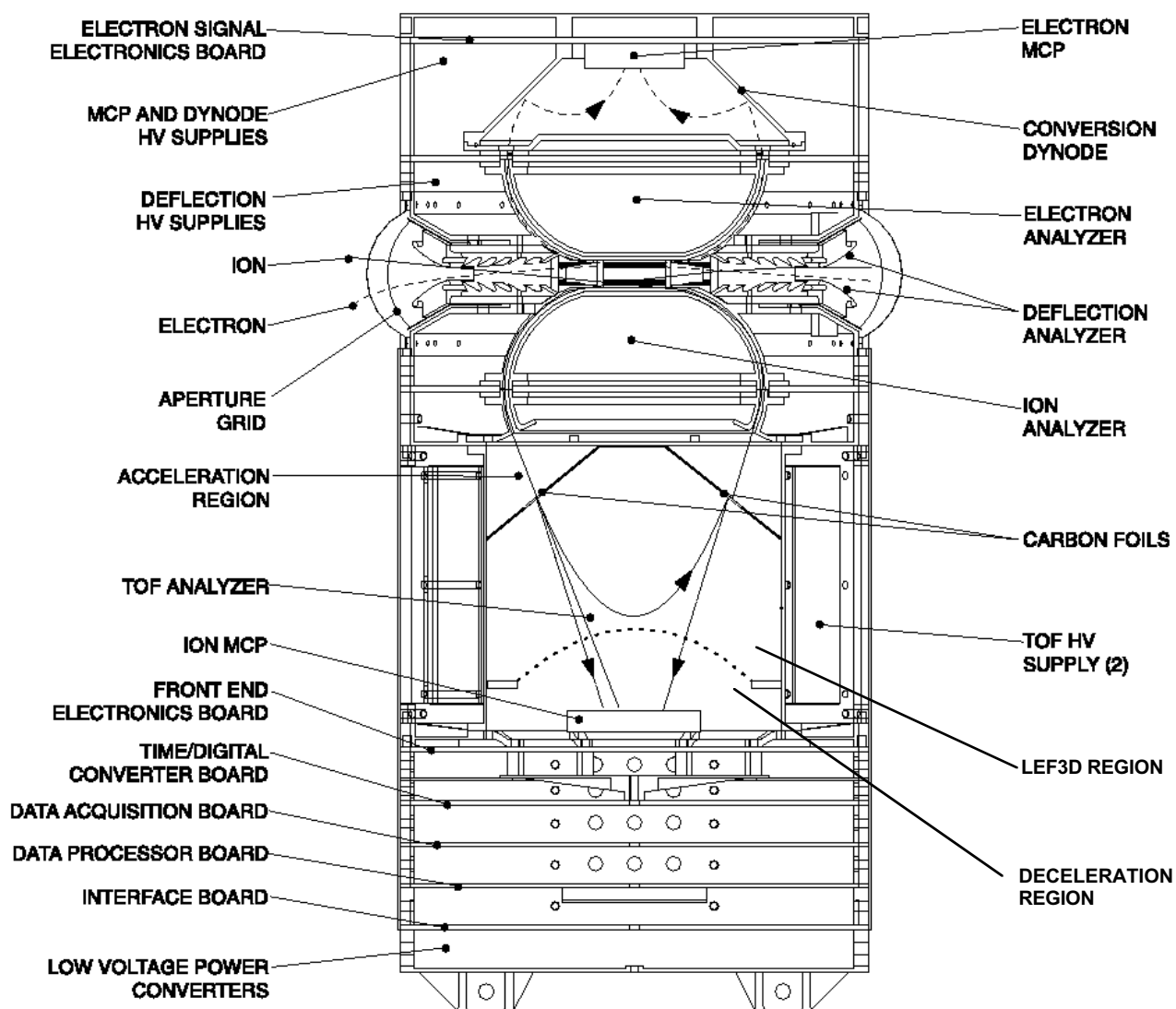
ELECTRON SIGNAL ELECTRONICS BOARD

MCP AND DYNODE HV SUPPLIES

DEFLECTION HV SUPPLIES

ION

ELECTRON

APERTURE GRID

ACCELERATION REGION

TOF ANALYZER

ION MCP

FRONT END ELECTRONICS BOARD

TIME/DIGITAL CONVERTER BOARD

DATA ACQUISITION BOARD

DATA PROCESSOR BOARD

INTERFACE BOARD

LOW VOLTAGE POWER CONVERTERS

ELECTRON MCP

CONVERSION DYNODE

ELECTRON ANALYZER

DEFLECTION ANALYZER

ION ANALYZER

CARBON FOILS

TOF HV SUPPLY (2)

LEF3D REGION

DECELERATION REGION

Figure 3 Schematic cross section of PEPE

Electrons transit the curved plates if their energy and direction match those that are allowed by the current voltage settings on the deflectors and curved plates. Once they exit the plates they strike a secondary emitter. The secondaries are then focused onto a micro-channel plate (MCP) detector stack. The use of the secondary emitter allows the design to use a smaller MCP than would otherwise be possible. The angle at which the electron entered PEPE is determined by discrete anodes behind the MCP.

When ions exit their set of curved analyzer plates, a large negative potential accelerates them into thin carbon foils. The foils form the entrance to the time-of-flight mass/charge analyzer. Electrons that are released by the passage of the ion through the foil are accelerated onto the outer annulus of the MCP stack at the bottom of the TOF section. They all take a uniform time of about 2ns to get to the MCP. There they start a clock that will be used to determine the time-of-flight for the ion that released them. Discrete anodes behind the MCP also determine the azimuthal angle at which the ion entered PEPE. Ions are generally neutralized by their passage through the foils. In this case they continue down the TOF section until they (with high probability) strike the center section or stop section of the MCP. This stops the clock and standard time-of-flight mass spectroscopy, with the knowledge of the ion s initial energy to determine its velocity, is used to determine the ion s mass. Mass resolution $M/\Delta M$ is only about 4 for this process. If the ion remains charged and it s energy is not too large to be turned around by the high voltage on the curved grid (heavy dotted line in Figure 3) it will bounce in the linearly increasing electric field just as a mass on a spring would. The time for one half oscillation of this bounce is independent of energy or angle of flight of the ion so the TOF is proportional to the square root of the mass/charge. Ions that do bounce hit a secondary emitter at the top of the TOF section and the resulting electrons are drawn to the center stop portion of the MCP. The mass resolution in the case is about 20.

All three regions, acceleration, LEF3D, and deceleration, of the TOF section use ceramic cylinders with resistive coatings to produce in them a uniform electric field but only
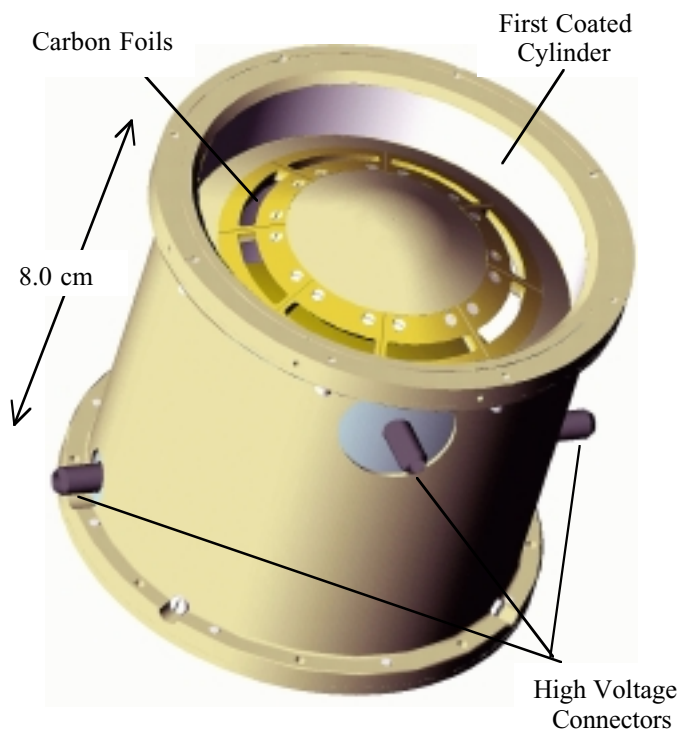
Carbon Foils

First Coated
Cylinder

8.0 cm

High Voltage
Connectors

Figure 4 PEPE TOF section

the center section requires the coating to have varying thickness to produce the linearly increasing electric field.

3. NEW TECHNOLOGIES

High Voltage Design

High voltages from a few kV to +/-15kV are needed to focus ions and electrons and power the detectors for the charged particles of interest in PEPE. The use of high voltages usually requires large spacings between focusing elements to allow the gap distances necessary to prevent high electric field breakdown and emission. Unfortunately, this usually leads to a large instrument with a mass increase corresponding to the increased size. PEPE uses high strength metal plated plastics and resistively coated ceramics in high voltage subsystems. This reduces the part count, mass, complexity, and assembly time. Where metal mechanical parts are used at high voltage, they were electro-polished as opposed to mechanically polished. The surface finish is not as fine but seems quite adequate to prevent high voltage breakdown.

High voltage power supplies

PEPE uses high voltage power supplies, produced by Pat Casey s group at Southwest Research Institute, with advanced miniaturized multipliers and small, lightweight packaging that uses metalized plastics and parylene coatings. This allows them to be enclosed in small plastic boxes that have been metalized to provide chassis ground and electro-magnetic field protection in a much smaller and lighter package than ever flown before. These power supplies were also specially designed to mate directly into the electro-optical elements which they power. They use spring mounted sockets which allow them to plug into commercial off the shelf (COTS) electrical connection pins as shown on the ion mass analysis section in Figure 4. This way the power supply itself replaces both the cabling and the connector normally used to give power supplies the ability to connect and disconnect to the elements they power. A small COTS electronics pin is used because it guarantees a definite low insertion force connection with spiral multi-wire high reliability sockets. The spring-loaded connector can move freely over a distance of about +/-0.4mm because a thin insulated wire inside the box is used to connect to the multiplier output. Unshielded wire would not be possible external to the power supply box because without a ground shield it would violate electro-magnetic cleanliness requirements. With a shield the wire and connector would be much longer and too large to mate to a small pin with the required positive coupling. Small pins with only insulated coupling sleeves are essential to keep the connector size down. Floating sockets allow these small connecting pins to survive relative motions between the optical sections and the power supply housing during launch vibration. Electro-magnetic cleanliness is maintained despite the use of an unshielded connector because the grounded power supply box is almost in contact with the ground shield of the electro-optics. These power supplies do not require potting and the +/-15kV supplies are each 150 grams and the size of a deck of playing cards. Figure 5 shows a 15kV power supply and Figure 6 shows a deflection supply that has been built into the electro-optics that house it.

Time-of-flight section

The TOF section is made by coating the hollow ceramic cylinders that line the ion flight path of the instrument with a resistive coating. This allows the cylinders to be coated with varying thickness to produce, in a very small area, the linearly increasing electric field and constant electric fields needed for the ion analysis. Using this technology, the standoff distances usually required to safely maintain voltages as high as +/-15kV are reduced by an order of magnitude over standard techniques. The resistive coating
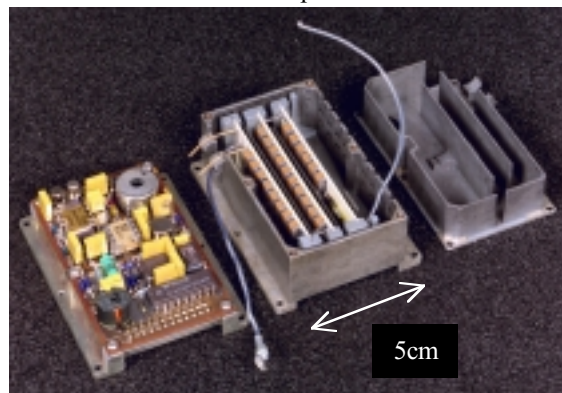

5cm

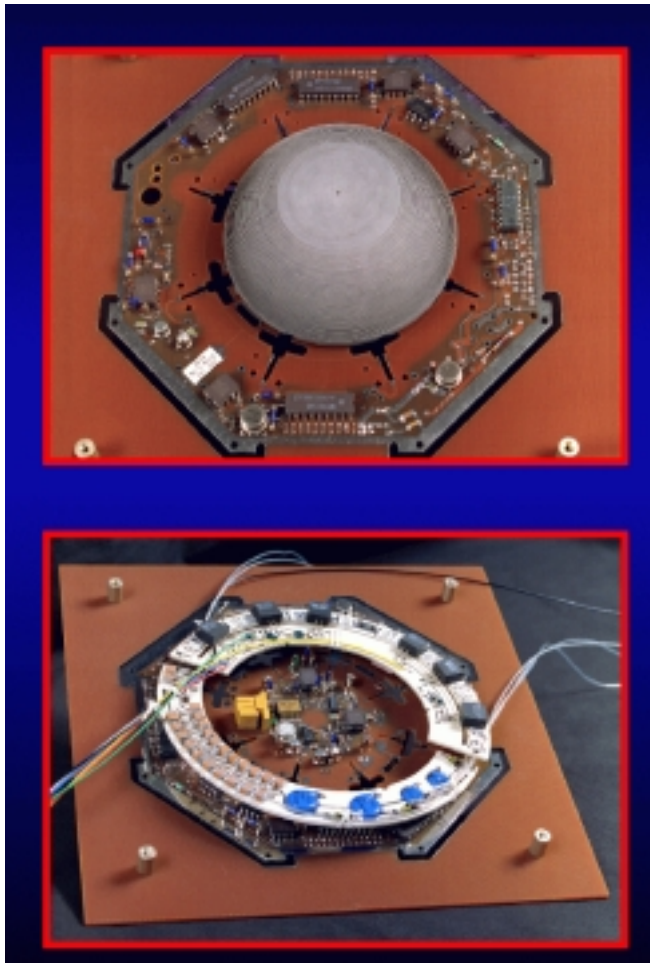**Figure 5** A PEPE 15kV Power Supply

Figure 6 A Deflection High Voltage Power Supply

also prevents scattered ions that impinge on the walls from charging the insulating ceramics which would then deflect ions unpredictably.

The coating process is a multi-step vapor deposition method that lays down a uniform resistive coating and ensures that the entire edge surface of each cylinder makes electrical contact with the voltage input ring with which it is in contact. The cylinder is first fitted into a masking jig which covers all but the ends and a few tenths of a millimeter of the inside of the hollow cylinder. This assembly is then placed in an evacuated bell jar where chromium is vapor deposited on one edge. The process is repeated for the other end of the cylinder. Once both ends are uniformly plated with a conductor, the resistive material is laid down on the inside of the cylinder. A new jig is fitted to the cylinder so that only the inside surface is visible. This assembly is then put in a bell jar with an oxygen atmosphere where chromium is evaporated onto the surface but, because of the presence of oxygen, a resistive chromium oxide coating is instead deposited. The distance from the cylinder to the evaporation boat determines whether the resistive coating is uniformly deposited or has a thickness which varies as the desired linear electric field requirement of $R \propto Z^2$. Here R is the resistance measured at a ring placed on the coating parallel to the edge of the cylinder and Z is the distance to one edge of the cylinder. The acceleration and deceleration cylinders are given a uniform chromium oxide coating.

The process involves balancing the distance to the evaporation boat, the speed of deposition, the oxygen pressure, and the thickness of the coating to produce a resistive coating in the desired range of total resistance. Total resistance, R_{tot}, must lie within the range $10 G\Omega \leq R_{tot} \leq 1 T\Omega$. R_{tot} should be large enough to ensure that the current drain from the power supplies is minimized because of the extreme limitations on power and so that power dissipated in the coatings does not cause them to heat significantly. The upper bound of R_{tot} insures that charge will not build up on the coated surfaces from an intense ion beam.

Chip-on-board Electronics

The MCPs used in PEPE can detect single particle impacts and produce signals which can be used to time that impact to better than 1ns. However they can produce signals with more than two orders of magnitude of dynamic range. Producing accurate timing information from small (few x 10^7 electrons) yet widely varying pulses in a noisy environment near a data processing unit is very challenging. The front-end electronics (FEE) for the ion mass section was newly designed using a coded anode and chip-on-board circuits to amplify and discriminate the signals. After some difficulty with infant mortality in these parts due to wire bond failure, they have performed flawlessly. Future models may be double wire-bonded to avoid the infant mortality problems. Rework was not a problem with these parts because they attach to the main boards via sockets. This is a very low cost and effective method to produce custom miniaturized circuits and it has proven its flight worthiness. The FEE used differential signals and referenced chassis ground for both shielding and signal discrimination. This method also has proven that it can save time and money over older techniques that sought to separate chassis and signal grounds. In these older systems signal-to-noise problems can be extensive and expensive to find and solve after integration.
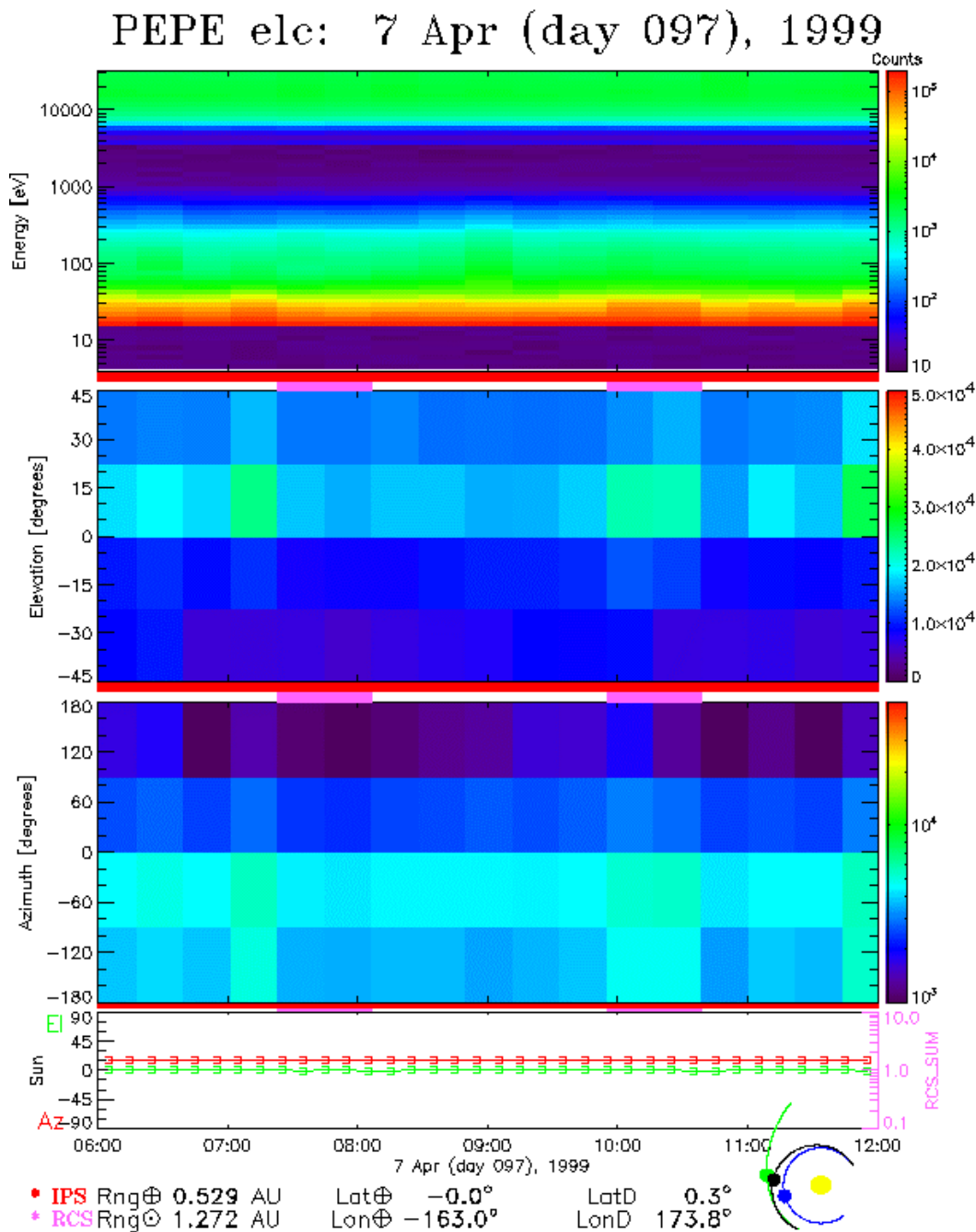
Figure 7 Electron Spectrogram for 6 Hours on a Day IPS Was Running

instruments of this type. Although many techniques and technologies were newly developed for PEPE the instrument concepts and objectives were either well known or developed for the CAPS instrument. This allowed software and design techniques to be applied successfully with little or no prior testing. Some custom parts were specially made for the CAPS instrument and required several design and test iterations for CAPS but could be used unchanged in PEPE. Electronic parts from CAPS that were surplus were used after the Cassini mission was launched. Also many design elements from CAPS were used in PEPE to save cost. If redesign of all systems on PEPE were required, the instrument could not have been produced within the time or cost allowed. This means that although the design of PEPE is very innovative, much of the development of completely new instrument concepts was done in the CAPS LEF3D Ion Mass Spectrometer (IMS) [7],[8], and could not be accomplished in the time and monetary budgets allowed for PEPE. In all likelihood completely new instrument concept development must be left for longer-term programs or instrument development programs such as NASA s Planetary Instrument Definition and Development Program (PIDDP). However the resource and cost savings from using new technology in a well known type of instrument is very significant and has rarely been attempted at the pace and impact level seen in PEPE. The new techniques validated in PEPE will save time and money as well as resources on future missions even when PEPE itself is not flown. Initial development is always more expensive than follow-on use of a technology so future use of these methodologies should have a strong positive impact on

4. COST SAVING TECHNIQUES

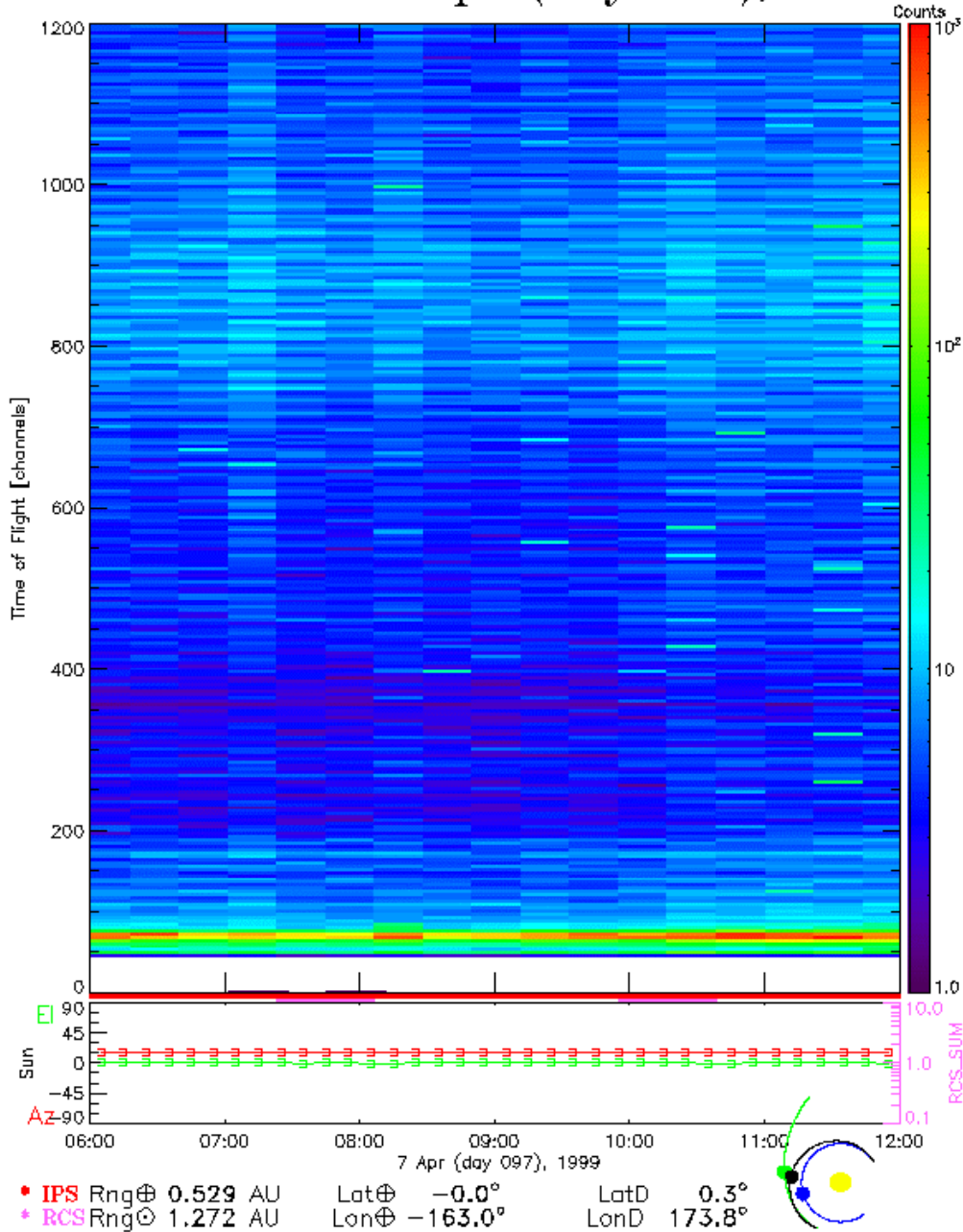*Short Development Time*

PEPE was built in just over two years. This compares with the NASA Cassini mission CAPS instrument which took almost ten years to produce. The difference in cost was closely tied to the difference in development time; however such a quick development period for PEPE was only possible because much time and effort had already been put into the CAPS instrument. A team was on hand that was very knowledgeable in construction, design, and testing of

Figure 9 Time of Flight Spectrum Same Time Period as Figures 7 and 8

DS1 project management. PEPE was a Category III instrument meaning that if it did not work it would not impact the mission as a whole. This allowed project managers to keep reviews and paperwork to a minimum, saving both time and money for all the organizations involved. DS1 personnel also were extremely helpful with parts procurement and requirements. Project management was flexible and judicious in their requirements.

Another very important part of the fast development and low-cost in PEPE was the use at both LANL and SwRI of science principal investigators who doubled as project task managers. This allowed them to be involved in every aspect of the design and construction. Additionally it streamlined the design-to-construction phases because all of the design criteria and construction techniques were centralized in one person who could make decisions on design, technology, and allowable risk with full knowledge of the impact on the instrument and desired science.

future space plasma spectrometers. Some of the more generic aspects of PEPE such as the use of COB electronics and high levels of electronic and mechanical parts integration can be used to improve packaging in many different types of instrumentation. Embedded sensor and electronics packaging that can be used even near contamination sensitive detectors can be used in types of sensors ranging from optical to ion and neutral particle detectors.

Management

Another aspect of the cost savings realized on PEPE was the

5. PERFORMANCE

PEPE weighs 5.5kg, uses 9.5 to 10.5W and is capable of telemetry rates from 50-1024 bits/s. This compares favorably with instruments such as CAPS which weighs 23kg, uses 16.4 to 21W and has a standard telemetry rate of 16k bits/s. PEPE has been taking data since December 1998 and appears to be in good working order. Its observations can be divided into several plasma regimes.

Solar Wind During most of its time onboard the DS1 mission, PEPE has had the solar wind available for

calibration and testing purposes. Comparison with instruments on the Wind spacecraft shows that the calculated sensitivity for PEPE is very nearly correct at $6x10^{-4}cm^2$-sr-eV/eV total for both electrons and ions. PEPE was not designed with solar wind science as its primary mission because of the beam-like characteristics and high charge state ions in the solar wind which do not require the sky scanning of PEPE and do not provide high resolution bounce mass spectra for most ions because the multiply charged ions of the solar wind generally exit the foils with lowered charge state and then cannot be turned around by the electric field in the LEF3D section. PEPE was designed for plasmas with low charge states and complicated masses and angular spreads such as those near planetary bodies. Nevertheless, the solar wind acts as an excellent source for instrument calibration and there is interest in scientific measurements by PEPE of the solar wind because of DS1 s location in space and the mass resolution capability.

Figures 7, 8, and 9 show data taken in the solar wind with the ion engine on. The narrow solar wind energy spectrum is clearly visible in Figure 8 at ~1keV. The low energy particle spectra from the ion engine is visible in Figures 7 and 8 as a narrow line at about 20eV. The electron spectra show a rise in electron flux at high energies above about 3keV which is due to some internal emission. The ion solar wind beam is clearly visible at 1keV in Figure 8. The H^+ and He^{++} from the solar wind beam are evident in the TOF plot in Figure 9 at about 70 and 140 TOF channels respectively. Each time-of-flight channel corresponds to a 750ps increase in ion time-of-flight.

Ion Engine PEPE measures the conditions induced by the ion engine s effluent xenon plume and can see other materials sputtered off the engine s interior by the xenon. Figure 9 shows a day where the ion engine was fired continuously. Xenon appears as a broad diffuse band at about 800 TOF bins. A faint line of molybdenum can be seen at ~670 bins. The xenon output is also visible at ~20eV in Figure 8.

Comets Unlike the encounter with asteroid Braille, PEPE should have adequate count rates at the two comets, Wilson-Harrington and Borrelly, that DS1 will flyby in 2001. The chances of detecting an asteroid were small and it is not surprising that no signal stands out above noise during the Braille encounter. Outgassing rates are significantly higher at a comet so the ion flux should be easily measurable. The TOF section was designed to analyze the relatively low energy, low charge state, plasmas near a planetary body such as a comet and should produce exciting results.

Future PEPE has been running at reduced voltage on the TOF section because it needed time to outgas sufficiently to hold the full design voltages of +/-15kV. Spacecraft command time was not available for these voltages to be raised until after the flyby of asteroid Braille. The attempt to raise the PEPE TOF voltages resulted in some damage to the TOF section because of a software error that increased voltages too quickly. The positive voltage was +8kV and will now be +5kV. The negative voltage can be increased beyond the —8kVat which it was originally operating. An increase in this voltage should improve PEPE s sensitivity

and mass resolution capability by decreasing scattering in the foils. High resolution analysis will be restricted to ions entering the instrument with less than ~5keV energy. PEPE should still be able to make significant contributions to solar wind science and do new science at the comets.

6. CONCLUSIONS

PEPE has demonstrated many new technologies and techniques that will advance future space plasma instruments. Many of these techniques can be applied to instruments in other scientific areas. Their validation in space is sufficient to allow the use of these technologies and techniques in other instruments. These cost-effective, fast turn-around techniques can help to make smaller, faster, cheaper, better a reality. PEPE has shown that they work well in space. On Earth the management techniques employed in DS1 are also essential to future gains in instrumentation in efficiency. If smaller, cheaper, faster, better comes to mean that experienced people are exhausted and leave the field, the next generation of sensors will suffer increased costs and failures. It is essential that instrument and management teams work together to ensure that necessary paperwork and review requirements are fulfilled but do not impede the development of the instrument. A responsible manager s rejoinder to problems faced by outside teams is often to hold more reviews, but this can be dangerously short sighted since much time must be devoted to each review when hardware work needs to be done.

The PEPE science team is looking forward to many future discoveries with DS1 and PEPE.

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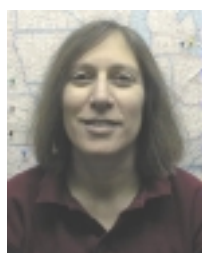
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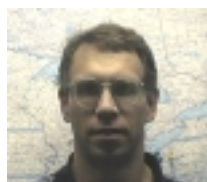
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